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Wasynczuk

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(54) **METHOD OF FABRICATING BULK CARBON NANOTUBE AND METALLIC COMPOSITES**

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D04H 1/00 (2006.01)
H01B 1/04 (2006.01)

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CPC ***H01B 1/04*** (2013.01); ***B32B 37/06*** (2013.01); ***C23C 16/06*** (2013.01); ***C23C 18/54*** (2013.01); ***H01B 1/02*** (2013.01); ***H01B 1/023*** (2013.01); ***H01B 1/026*** (2013.01); *B32B 2310/028* (2013.01); *Y10T 156/10* (2015.01); *Y10T 428/294* (2015.01); *Y10T 428/2938* (2015.01); *Y10T 428/2958* (2015.01); *Y10T 428/30* (2015.01); *Y10T 442/2418* (2015.04); *Y10T 442/655* (2015.04); *Y10T 442/657* (2015.04)

(58) **Field of Classification Search**

CPC B82Y 30/00; B82Y 40/00; Y10S 977/742; Y10S 977/75; Y10S 977/752; Y10S 977/842; C01B 2202/02; C01B 2202/08; H01L 21/28556

USPC 977/742, 750–752, 778, 784; 442/59, 442/110–116, 228–231, 316, 317; 428/378–381, 389; 427/123–125, 427/255.28, 250, 431; 156/60, 73.1; 204/192.1

See application file for complete search history.

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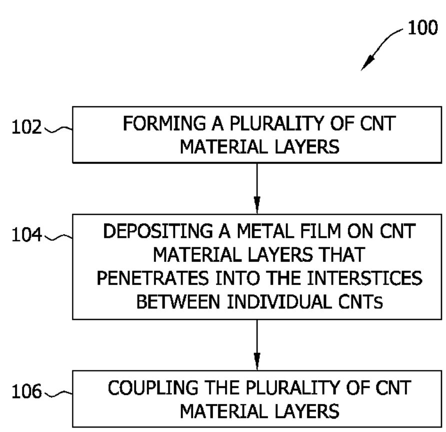
(57) **ABSTRACT**

In one embodiment, a bulk carbon nanotube and metallic composite is provided. The bulk carbon nanotube and metallic composite includes a bulk carbon nanotube material layer including a plurality of carbon nanotubes, and a metal film applied across the bulk carbon nanotube material layer. The metal film penetrates into the interstices between individual carbon nanotubes to reduce an electrical resistance between the plurality of carbon nanotubes.

12 Claims, 2 Drawing Sheets



(51) **Int. Cl.**

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B32B 37/06	(2006.01)
C23C 16/06	(2006.01)
C23C 18/54	(2006.01)

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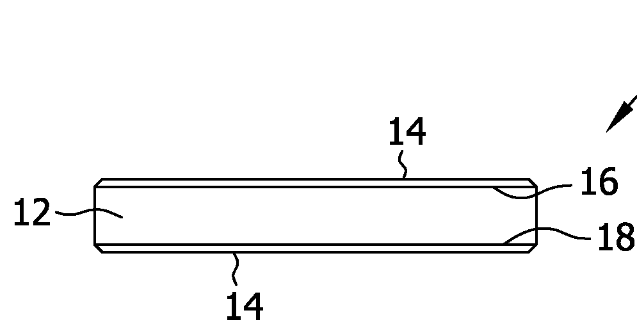

FIG. 1

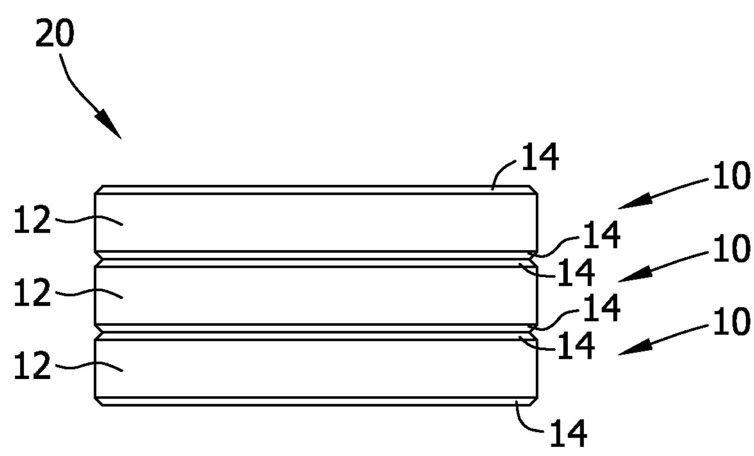

FIG. 2

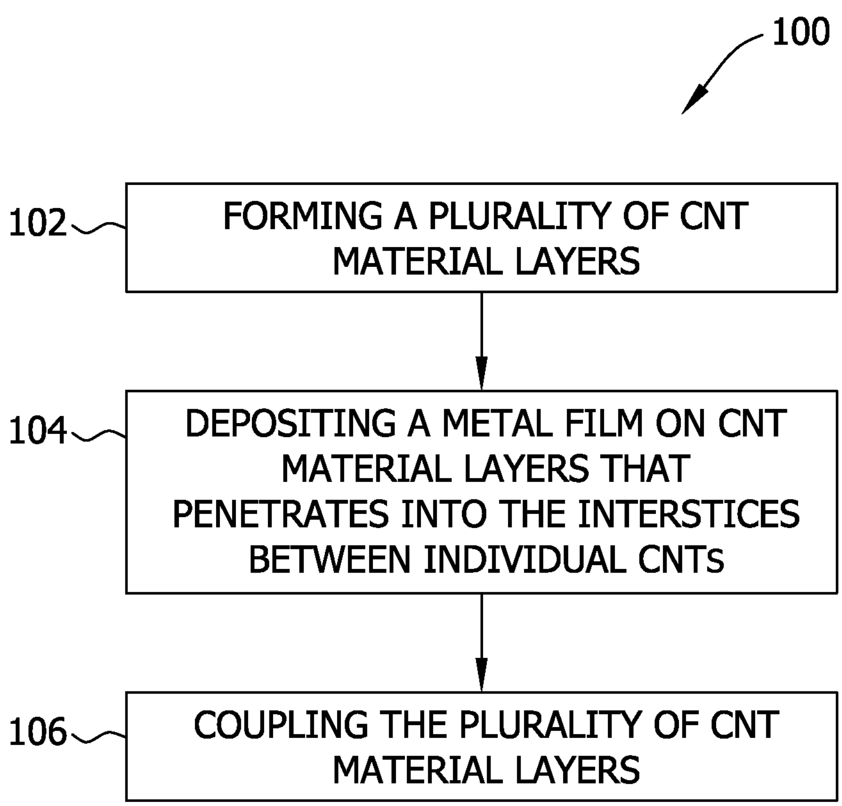
100
102
FORMING A PLURALITY OF CNT MATERIAL LAYERS
104
DEPOSITING A METAL FILM ON CNT MATERIAL LAYERS THAT PENETRATES INTO THE INTERSTICES BETWEEN INDIVIDUAL CNTs
106
COUPLING THE PLURALITY OF CNT MATERIAL LAYERS

FIG. 3

METHOD OF FABRICATING BULK CARBON NANOTUBE AND METALLIC COMPOSITES

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a divisional application of U.S. patent application Ser. No. 13/621,585, filed Sep. 17, 2012, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE DISCLOSURE

The field of the disclosure relates generally to composite materials and, more particularly, to bulk carbon nanotube and metallic composites.

At least some known carbon nanotubes (CNT) are formed from a one-atom thick sheet of graphite commonly referred to as "graphene". The sheet is rolled into a cylinder that has a diameter of the order of a nanometer and a length on the order of a micrometer. Known CNTs exhibit extraordinary strength and electrical properties, and are efficient conductors of heat. The two most common types of CNTs are single-walled carbon nanotubes (SWCNTs) that are formed from a single layer of graphene, and multi-walled carbon nanotubes (MWCNTs) that are formed from multiple concentric cylinders or a graphene sheet that is rolled around itself.

CNTs are lightweight and have a very high elastic modulus. The conductive properties of CNTs depend upon the diameter and the chirality of the hexagonal carbon lattice extending along the tube. A slight change in the winding of the hexagonal lattice along the tube can result in the CNT functioning either as a metal or a semiconductor. For example, hexagonal rows that are parallel to the tube axis produce a metallic structure known as an "armchair" configuration. In contrast, alternating rows of carbon bonds around the tube circumference produce a semi-conducting structure known as a "zigzag" configuration. Although individual CNTs may be highly electrically conductive, high contact resistance between multiple CNTs results in low electrical conductivity of bulk CNT materials.

BRIEF DESCRIPTION OF THE DISCLOSURE

In one aspect, a method of fabricating a bulk carbon nanotube and metallic composite is provided. The method includes forming a first bulk carbon nanotube material layer comprising a plurality of carbon nanotubes, and depositing a metal film across the bulk carbon nanotube material layer. The metal film penetrates into the interstices between individual carbon nanotubes to reduce an electrical resistance between the plurality of carbon nanotubes.

In another aspect, a method of fabricating a composite assembly is provided. The method includes forming a first bulk carbon nanotube material layer comprising a plurality of carbon nanotubes, and applying a metal film across an outer surface of the bulk carbon nanotube material layer such that the metal film penetrates through the outer surface and into interstices between individual carbon nanotubes to facilitate reducing an electrical resistance between the plurality of carbon nanotubes. At least a portion of the plurality of carbon nanotubes remain uncoated with the metal film.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is schematic view of an exemplary bulk CNT and metallic composite;

FIG. **2** is a schematic view of an exemplary bulk CNT and metallic composite strip; and

FIG. **3** is a block diagram of an exemplary method of fabricating a bulk CNT and metallic composite strip.

DETAILED DESCRIPTION OF THE DISCLOSURE

FIG. **1** illustrates an exemplary bulk carbon nanotube (CNT) and metallic composite **10** that includes a bulk CNT material layer **12** and one or more thin metal films or layers **14**. In the exemplary embodiment, bulk CNT layer **12** includes opposed first and second sides **16** and **18**, respectively, and a layer of metal film **14** is deposited across each side **16** and **18**. FIG. **2** illustrates an exemplary bulk CNT and metallic composite strip **20** that is fabricated by welding bulk CNT layers **12** together, as will be described in more detail. The methods described herein produce a bulk CNT and metallic composite strip **20** that has a high weight-normalized electrical conductivity, a high thermal conductivity, and a high mechanical strength.

In the exemplary embodiment, bulk CNT layer **12** is fabricated from a plurality of metallic CNTs (not shown), such as "armchair" CNTs, that are each oriented with a chiral angle that is substantially parallel to the tube axis of each CNT. When a graphene sheet (not shown) that forms each CNT is wrapped with an armchair chirality, each formed CNT has an increased metallic character and has an increased capability for tremendously high current density. Alternatively, bulk CNT layer **12** may include a number of semi-conductor CNTs (not shown) in addition to the metallic CNTs. In the exemplary embodiment, bulk CNT layer **12** is a non-woven sheet or a yarn. Alternatively, any other form of bulk CNT layer **12** may be used that enables composite **10** to function as described herein.

In the exemplary embodiment, metal film **14** is applied across CNT layer sides **16** and **18** and penetrates into the interstices between individual CNTs. In the exemplary embodiment, the amount of metal used to form metal film **14** is enough to facilitate low electrical resistance interconnects between a substantial number of the CNTs. In the exemplary embodiment, metal film **14** is a thin-film of aluminum that penetrates the bulk CNT layer **12** and coats a large fraction of the CNTs. Alternatively, metal film **14** may be any electrically conductive metal or combination of metals that enables bulk CNT and metallic composite **10** to function as described herein. In the exemplary embodiment, metal film **14** is applied directly across CNT layer **12** via chemical vapor deposition and/or electroless plating. As such, in the exemplary embodiment, the process facilitates depositing metal within the interstices of the bulk CNT layer. Alternatively, metal film **14** may be applied via a sputtering and/or a physical vapor deposition process. However, any other metal deposition process may be used that enables bulk CNT and metallic composite **10** to function as described herein.

In the exemplary embodiment, multiple bulk CNT and metallic composites **10** are coupled together via a welding process that forms a bulk CNT and metallic composite strip **20**. In the exemplary embodiment, and as shown in FIG. **2**, three CNT and metallic composites **10** are coupled together along their sides **16** and/or **18**. Additionally, CNT and metallic composites **10** may be joined in an end-to-end orientation (not shown). Moreover, any number of CNT and metallic composites **10** may be coupled together to form a bulk CNT and metallic composite strip **20** with any desired length, width and/or thickness. In the exemplary embodiment, CNT and metallic composites **10** are joined together via an ultrasonic welding process. Alternatively, CNT and metallic composites **10** are joined together via an ultrasonic additive manufacturing (UAM) process that sequentially couples layers of patterned metal together to produce net shape products having complex interior cavities.

FIG. **3** illustrates an exemplary method **100** of fabricating a bulk CNT and metallic composite strip **20**. Method **100** includes forming **102** a plurality of CNT material layers **12** from a plurality of single-walled carbon nanotubes (SWCNTs) and/or multi-walled carbon nanotubes (MWCNTs). In the exemplary embodiment, CNT material layers **12** are a non-woven sheet or a yarn. The method further includes depositing **104** a metal film **14** across one or more sides **16** and **18** of CNT material layer **12** to form a bulk CNT and metallic composite **10**. In the exemplary embodiment, metal film **14** is deposited by at least one of a chemical vapor deposition, an electroless plating, a sputtering, and a physical vapor deposition process. The method also includes coupling **106** multiple bulk CNT and metallic composites **10** together to form a bulk CNT and metallic composite strip **20**. In the exemplary embodiment, bulk CNT and metallic composites **10** are coupled together via at least one of an ultrasonic welding and an ultrasonic additive manufacturing process.

EXAMPLE

In one example, non-woven sheets of bulk CNT material layers **12** are fabricated from individual SWCNTs having a diameter between about 2 nm and about 5 nm, individual MWCNTs having a diameter between about 20 nm and about 50 nm, or a combination of both. Each bulk CNT layer **12** is formed with a cross-sectional thickness of between about 20 μm and about 100 μm. A bulk CNT and metallic composite **10** is formed by coating each side **16** and **18** of bulk CNT layer **12** with approximately 3,000 Å (0.3 μm) of metallic material. For example, in the exemplary embodiment, a metallic material such as aluminum, copper, nickel, titanium, silver, gold or chromium, or any combination thereof, may be used to form metallic composite **10**. Alternatively, any metallic material may be used that enables metallic composite **10** to function as described herein. The resulting bulk CNT and metallic composites **10** are coupled together via an ultrasonic welding process to form a bulk CNT and metallic composite strip **20**. The ultrasonic welding process facilitates reducing open space within composites **10** and reducing a thickness of each bulk CNT and metallic composite **10** by approximately 20%. As such, bulk CNT and metallic composite **10** has a decreased electrical resistance between individual CNTs and a decreased electrical resistance. In the example, bulk CNT and metallic composite strip **20** is fabricated with dimensions measuring roughly one cm wide, 10 cm long, and is one to several composites **10** thick.

As described herein, a bulk CNT and metallic composite is fabricated with an increased specific electrical conductivity that is superior to other materials such as copper and aluminum. In addition, the composite exhibits a high electrical conductivity, a high thermal conductivity, and a high mechanical strength. The bulk CNT composite formed with the above techniques reduces contact resistance between individual CNTs and reduced open space within each bulk CNT and metallic composite. Further, a plurality of bulk CNT and metallic composites are coupled to form a high strength, highly electrically conductive bulk CNT and metallic composite strip. The bulk CNT composite material having superior qualities makes it ideal for applications such as EMI shielding, wire conductors for power transmission line, spacecraft harness, and electric motors.

This written description uses examples to disclose the various embodiments, including the best mode, and also to enable any person skilled in the art to practice such embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A method of making a bulk carbon nanotube and metallic composite strip, the method comprising:

forming a first bulk carbon nanotube material layer including a plurality of carbon nanotubes;

depositing a metal film across the bulk carbon nanotube material layer, the metal film penetrating into the interstices between individual carbon nanotubes to reduce an electrical resistance between the plurality of carbon nanotubes to fabricate a first bulk carbon nanotube and metallic composite;

fabricating a second bulk carbon nanotube and metallic composite; and

coupling the first and second bulk carbon nanotube and metallic composites using at least one of an ultrasonic welding process and an ultrasonic additive manufacturing process to form a bulk carbon nanotube and metallic composite strip.

2. The method of claim **1**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using metallic carbon nanotubes.

3. The method of claim **1**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using at least one of single-walled carbon nanotubes and multi-walled carbon nanotubes.

4. The method of claim **1**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using at least one of a non-woven sheet and a yarn.

5. The method of claim **1**, wherein depositing the metal film comprises applying the metal film onto the bulk carbon nanotube material layer using at least one of a chemical vapor deposition process, an electroless plating process, a sputtering process, and a physical vapor deposition process.

6. The method of claim **1**, wherein depositing the metal film comprises applying at least one of aluminum, nickel, copper, titanium, silver, gold and chromium onto the bulk carbon nanotube material layer.

7. A method of making a bulk carbon nanotube and metallic composite strip, the method comprising:

forming a first bulk carbon nanotube material layer including a plurality of carbon nanotubes;

applying a metal film across an outer surface of the bulk carbon nanotube material layer such that the metal film penetrates through the outer surface and into interstices between individual carbon nanotubes to facilitate reducing an electrical resistance between the plurality of carbon nanotubes, wherein at least a portion of the plurality of carbon nanotubes remain uncoated with the metal film to form a first bulk carbon nanotube and metallic composite;

fabricating a second bulk carbon nanotube and metallic composite; and

coupling the first and second bulk carbon nanotube and metallic composites using at least one of an ultrasonic welding process and an ultrasonic additive manufacturing process to form a bulk carbon nanotube and metallic composite strip.

8. The method of claim **7**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using metallic carbon nanotubes.

9. The method of claim **7**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using at least one of single-walled carbon nanotubes and multi-walled carbon nanotubes.

10. The method of claim **7**, wherein forming the first bulk carbon nanotube material layer comprises forming at least a portion of the layer using at least one of a non-woven sheet and a yarn.

11. The method of claim **7**, wherein depositing the metal film comprises applying the metal film onto the bulk carbon nanotube material layer using at least one of a chemical vapor deposition process, an electroless plating process, a sputtering process, and a physical vapor deposition process.

12. The method of claim **7**, wherein depositing the metal film comprises applying at least one of aluminum, nickel, copper, titanium, silver, gold and chromium onto the bulk carbon nanotube material layer.

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